

The Proper Motion, Parallax, and Origin of the Isolated Neutron Star RX J185635-3754

Frederick M. Walter

Department of Physics and Astronomy, State University of New York, Stony Brook NY

11794-3800

fwalter@astro.sunysb.edu

ABSTRACT

The isolated neutron star RX J185635-3754 is the closest known neutron star to the Sun. Based on HST WFPC2 observations over a 3 year baseline, I report its proper motion (332 ± 1 mas yr^{-1} at a position angle of $100.3^\circ \pm 0.1^\circ$) and parallax (16.5 ± 2.3 mas; 61 pc). This proper motion brings the neutron star from the general vicinity of the Sco-Cen OB association. For an assumed neutron star radial velocity of -45 km s^{-1} , the runaway O star ζ Oph, the Upper Sco OB association, and the neutron star come into spatial coincidence $1.15 \pm .15$ million years ago. RX J185635-3754 may be the remnant of the original primary of the ζ Oph system. If so, the space velocity suggests that the neutron star received a kick of about 200 km s^{-1} at birth.

Subject headings: stars: neutron; stars: individual (RX J185635-3754); stars: kinematics; open clusters and associations: Sco-Cen

1. Introduction

Most neutron stars known in our galaxy have been identified either because they are accreting from a binary companion or because their rapid rotation and strong magnetic field produces a radio or X/ γ -ray pulsar. Studies of accreting neutron stars or pulsars tell us far more about accretion and magnetospheric physics than they do about the intrinsic properties of neutron stars. Based either on pulsar birthrates (Narayan & Ostriker 1990), or on the number of supernovae needed to account for the heavy element abundance of the galaxy (Arnett, Schramm, & Truran 1989), there are 10^8 to 10^9 neutron stars in the galaxy. There are a few hundred accreting neutron star binaries currently known, and about 1000 radio pulsars. The accreting neutron stars and the pulsars are not representative of the vast majority of the neutron stars in the galaxy.

Representatives of the non-accreting, non-pulsing variety of neutron stars have been eagerly sought over the past decade (e.g., Greiner 1996; Manning, Jeffries, & Willmore 1996; Belloni, Zampieri, & Campana 1997), and some likely candidates have been identified. These radio quiet neutron stars (see Caraveo, Bignami, & Trümper 1996 for a review) form an inhomogeneous group.

Some radio quiet neutron stars are associated with young supernova remnants. These may be radio-quiet because their radio emission is beamed (e.g., Brazier & Johnston 1999), they are highly magnetized yet slowly rotating (e.g., Vasisht et al. 1997), or because they are not highly magnetized at birth because the fallback submerges the field (Geppert, Page, & Zambias 1999). Examples of young, radio quiet neutron stars include RX J0822-4300 in Pup A (Gaensler, Bock, & Stappers 2000) and the central point source in Cas A (Chakrabarty et al. 2000). These are still young and hot, and are X-ray-bright, with X-ray luminosities of order 10^{35-36} erg s⁻¹.

Other radio quiet neutron star candidates are not associated with supernova remnants, and may be old. Isolated neutron stars cool quickly (e.g., Tsuruta 1998), within about 1 million years (Myr), so most neutron stars should be faint (of order 10^{31} erg s⁻¹ or less), and difficult to find. A handful of old neutron star candidates have been discovered as X-ray sources in ROSAT images (cf. Caraveo et al. 1996). These are soft X-ray sources with approximately black body spectra, temperatures (kT) of 10 to 100 eV, and $\frac{f_x}{f_{opt}}$ ratios in excess of 1000. Although some may be magnetars (Thompson & Duncan 1995; Heyl & Kulkarni 1998), others may be bona-fide old, isolated, weakly magnetized neutron stars. Such old isolated neutron stars afford the opportunity to study the atmospheres of neutron stars (e.g., Pavlov et al. 1996b, Rajagopal & Romani 1996). It is in principle possible to determine the composition, surface gravity, and angular diameter of an isolated neutron star from analysis of its spectrum. This can yield both the mass M and radius R , and place constraints on the nuclear equation of state (e.g., Lattimer & Prakash 1998, 2000). While it is possible to study the surfaces of pulsars by observing the unpulsed, thermal component (e.g., Pavlov, Stringfellow, & Cordova 1996a), or to determine the mass from the orbital dynamics of the accreting matter (Miller, Lamb, & Psaltis 1998; Kaaret, Ford, & Chen 1997; Zhang, Strohmayer & Swank 1997) or from modelling X-ray bursts (Haberl & Titarchuk 1995; Strohmayer et al. 1997), it is easier to do so for an isolated non-pulsing neutron star.

The brightest of these isolated neutron star candidates is RX J185635-3754 (Walter, Wolk, & Neuhauser 1996). Its optical counterpart is a blue object with $V \approx 25.7$ (Walter & Matthews 1997). On the basis of its 57 eV temperature, nearly thermal spectrum, and projection against the ≈ 130 pc-distant R CrA molecular cloud (Maracco & Rydgren 1981),

it would have an emitting area smaller than about 700 km^2 if a blackbody. In the presence of an atmosphere, the emitting area, or radius, must be larger than the blackbody of the same temperature. There is no evidence for X-ray pulsations, and it is radio-quiet. We observe emission from the entire surface of a neutron star, and not from a heated polar cap.

The important heating processes in an isolated neutron star are heat loss from the hot interior (reviewed by Tsuruta 1998) and accretion from the interstellar medium (e.g., Blaes & Madau 1993; Turolla 1997). In standard cooling models the surface temperature is expected to plummet below 10^6 K within 1 Myr, but various surface reheating schemes have been proposed (e.g., Larson & Link 1999) to keep the surface hot for longer times. Heating via accretion from the interstellar medium does not decay with time (although it will vary with the density of the local interstellar medium), but if the space velocity exceeds about 15 km s^{-1} , Bondi-Hoyle accretion from the interstellar gas should be negligible.

The uncomplicated, isolated, radio quiet neutron star RX J185635-3754 affords the opportunity to study the immaculate surface of a neutron star. To interpret the spectral energy distribution properly, and to determine its radius, we need its distance. Here I report on the astrometric analysis of 3 images of RX J185635-3754 taken with the Hubble Space Telescope WFPC2 detector over the course of 3 years. These images reveal the parallax and proper motion of the target.

2. The Data

We obtained 3 sets of observations with the HST WFPC2 camera (Table 1). The first epoch images were described by Walter & Matthews (1997). The images were taken near the times of maximum parallactic displacement, which occurs on 3 October and 30 March. The images were dithered using the standard 5.5 pixel diagonal shift. The first and third observations each consist of 4 images; we obtained 8 images during the second observation. The target is located near the center of the planetary camera (PC). I did not analyze the images from the other cameras. I discuss here the images taken through the F606W filter. We also obtained images through the F178W, F300W, and F450W filters. The spectrophotometry will be discussed elsewhere.

3. Analysis Technique

I analyzed the re-calibrated images delivered through the Multimission Archive at STScI (MAST). For each of the three observations I produced a median-filtered, co-added

image for astrometric and photometric analysis. I did this by rebinning the data to twice the nominal scale, shifting the dithered PC images by the nominal offsets, rebinning the images back to the nominal scale, and stacking the images. After median-filtering the images to remove cosmic rays, I co-added the images. All the analysis was performed using software written in the IDL language, incorporating some software from the IDL astronomy users library (Landsman 1995).

Forty three objects are common to the three PC images, including the target (Table 2) but excluding the brightest stars. Four of these objects appear extended, and are likely to be galaxies. The approximate R-band magnitudes from aperture photometry range from 18.8 to 26.8. In the images, stars C, D, F, L, and M of Walter et al. (1996) appear to be overexposed. Star 20 of Campana et al. (1997) is clearly a galaxy; their star 25 is a visual pair with a separation of 0.2 arcsec.

I measured the positions of the objects by fitting two dimensional Gaussian and Lorentzian line profile, and by fitting one-dimensional Gaussians independently in RA and DEC. The two dimensional fits utilize the MPFIT2DPEAK IDL procedure¹. The Lorentzian profile is more sharply peaked than the Gaussian profile, and is somewhat better matched to the HST PSF (as estimated by the χ^2 values for the fits). The two dimensional fits employ flat backgrounds. The advantage of the one-dimensional fits is that I can fit a varying (up to second order) background. This can improve the quality of the fit in confused regions, near bright stars, or near diffraction spikes.

Prior to fitting the data I corrected for the 34th row error (Anderson & King 1999) and for the geometric distortions in the PC camera (Holtzman et al. 1995). These detector coordinates are converted into celestial coordinates using the astrometric information in the FITS header. The absolute positions depend on the particular guide stars used for each observation. The positions listed in Table 2 are those measured from the 1996 October 6 image. Relative to that image, the coordinates measured in the subsequent two images are offset by (+3.4,+0.6) and (−0.6,+0.3) arcsec in RA,DEC.

The astrometric reductions are done in X-Y coordinates, corrected for detector distortions. I unrolled the images using the orientation given in the FITS header, so that X,Y correspond to RA,DEC. Direct comparison of the images shows no evidence of any residual roll or changes in the nominal plate scale of 0.0455 arcsec pixel^{−1}.

The position of a star at epoch k , relative to the initial position, is given by

¹<http://cow.physics.wisc.edu/~craigm/idl/fitting.html>

$$\begin{aligned} X_k - X_0 &= O_X(k) + PM_X dT_k + \pi_X(dT_k)/d, \\ Y_k - Y_0 &= O_Y(k) + PM_Y dT_k + \pi_Y(dT_k)/d \end{aligned}$$

where X_k , Y_k are the observed position during observation k , O is the systematic offset between the two coordinate systems, dT_k is the elapsed time since the first observation, PM is the proper motion, π is the magnitude of the parallactic displacement at one pc, and d is the distance. The position angle of the major axis of the parallactic ellipse is 83° .

I determined the systematic offsets O_X, O_Y between the observations (see above) by taking the weighted mean of the differences in the X and Y positions after rejecting positions that are discrepant from the mean at more than 3σ . The weighted mean and median offsets agree to better than 2 milli-arcsec. There was no evidence for any significant deviations from the nominal roll angle. Removing the offset leaves a coupled set of 2 equations with two unknowns in each dimension, which I then solve for the parallax and proper motion.

4. Results

The measured motions of RX J185635-3754 are summarized in Table 3, and the motion is shown in Figure 1. The three sets of measurements yield results which agree within their uncertainties. In Table 3 I quote 68% and 95% joint confidence uncertainties on the derived quantities. To determine the uncertainties, I ran a Monte Carlo simulation, selecting positions at random from a normally-distributed sample with mean equal to the measured offsets and variance equal to the measurement error.

RX J185635-3754 star is moving just south of east at a rate of $1/3$ of an arcsecond per year². The parallax of 16 milli-arcsec (32 milli-arcsec full amplitude) is detected at greater than 7σ . Note that the directions of the proper motion and the major axis of the parallactic ellipse are co-aligned to within 17° . A 1% error in the magnitude of the proper motion yields a 12% uncertainty in the parallax. The joint confidence contours (Figure 2) show the correlation.

The components of the space motion are illustrated in in Figure 3. Figure 4 shows the measured positions and the parallactic ellipse after subtracting the proper motion.

Since the determinations of the proper motion and parallax are done with respect to all the objects in the image, it is possible that they can be biased by systematic motions

²This proper motion was first detected using the two ROSAT HRI observations. Walter & An (1998) reported a proper motion of 0.4 ± 0.2 arcsec yr^{-1} in a southeasterly direction.

of the comparison stars. These would manifest themselves as systematic offsets in the two mean positions. Given the brightnesses of the comparison stars, it is unlikely that there will be any detectable mean space motions or parallax. The brightest star, with $F_{606W} \approx 18.9$, must be at a distance modulus in excess of 6 if an M dwarf (the $B - R$ color suggests an F dwarf at a distance modulus in excess of 10, although it could be a closer white dwarf). The bulk of the comparison stars, with $R > 23$, unless very heavily reddened, are more distant than 1 kpc if dwarfs. In this direction ($l=0^\circ$, $b=-20^\circ$), it is likely that we are seeing mostly evolved stars in the galactic bulge. Consequently it is unlikely that there is any detectable, systematic motion of the comparison stars.

5. Discussion

The proper motion is consistent with the expectation that RX J185635-3754 is a nearby neutron star. The proper motion is sufficiently large that accretion from the interstellar medium, which scales as v^{-3} , produces negligible heating of the surface. In the Blaes & Madau (1993) formalism, accretion heating for a surface filling factor $f=1$ and an interstellar density $n_H=1 \text{ cm}^{-3}$ can account for only about 1% of the observed luminosity of the star.

5.1. Parallax and Implications for the Radius

The distance of $61 \pm 9 \text{ pc}$ is small; this is likely the nearest known neutron star to the Earth. The distance is an important parameter to know well, since both the space velocity and the inferred radius scale with the distance.

Walter et al. (1996) claimed a firm upper limit to the distance of about 130 pc, based on the low X-ray absorption column of $1.4 \times 10^{20} \text{ cm}^{-2}$ ($E_{B-V}=0.02 \text{ mag}$). Even though our analysis of the multi-wavelength spectrum (An 2000; Pons et al., in preparation) suggests a higher column of about $2 \times 10^{20} \text{ cm}^{-2}$, this is still comfortably less than that expected from the CrA molecular cloud in this direction. However, a column of $2 \times 10^{20} \text{ cm}^{-2}$ implies a mean interstellar density of 1 cm^{-3} , which is substantially higher than the mean in the local ISM. This would be worrisome, were it not for the fact that Knude & Høeg (1998) show that substantial reddening exists in front of the CrA cloud, with extinctions E_{B-V} of up to 0.1 for stars within 50 pc.

At this distance, the blackbody radius $R_\infty \left(\equiv \frac{R}{\sqrt{1 - \frac{2GM}{Rc^2}}} \right)$ of the object is 3.3 km using

the 57 eV temperature reported by Walter et al. (1996). The X-ray and optical data are better fit by model atmospheres of heavy element composition (An 2000; Walter et al. 2000; Walter & An 1998; Pons et al., in preparation), with $kT \sim 49$ eV and an angular diameter $R_\infty/d = 0.18 \pm 0.05$. In this case, $R_\infty = 11.2 \pm 3.4$ km. I caution that the inferred radius is model-dependent, and cannot be considered a firm measurement until the surface composition is measured observationally from good-quality X-ray spectra. Nevertheless, the radius suggests that we are indeed viewing the entire surface of the neutron star, and not just a heated polar cap.

5.2. History of this Neutron Star

The proper motion of the neutron star provides clues to its origin. If the age is small enough one might hope to trace the star back to a plausible birthplace and place constraints on the possible progenitors and the evolutionary history of this neutron star. Here the proper motion directs us back towards the Sco-Cen OB association, a source of supernovae during the past few million years (de Geus, de Zeeuw, & Lub 1989), and the apparent birthplace of the runaway O star ζ Oph (Blaauw 1991, 1993). To clarify the relation, if any, of RX J185635-3754, the Sco-Cen OB association, and ζ Oph, requires running the space motions of these objects backwards through time.

de Zeeuw et al. (1999) catalog members of the Upper Sco and Upper Cen-Lup associations, along with mean distances and radial velocities of the associations. I went back to the listings for the individual members in the Hipparcos Catalog (ESA 1997), and confirmed the mean proper motions. de Zeeuw et al. quote diameters of ~ 14 and 27 degrees for the two associations. Although the associations are almost certainly expanding and dispersing, I assume a constant radial extent in the analysis below.

I take the parallax and proper motion of ζ Oph (HD 149757) from the Hipparcos Catalog (ESA 1997). I adopt the radial velocity of -9 km s $^{-1}$ quoted in the Hipparcos Input Catalog (Turon et al. 1993). Evans (1979) quotes a radial velocity of -15 km s $^{-1}$. van Rensbergen et al. (1996) quote a peculiar velocity of 18 km s $^{-1}$ with respect to the Sco-Cen OB association, apparently assuming a single radial velocity for the association. In light of the range in the radial velocities, and the difficulty of establishing the radial velocity of a hot star with such rapid rotation, I adopt an uncertainty of ± 5 km s $^{-1}$.

I examine the space motions by converting all motions to heliocentric Cartesian coordinates. Uncertainties in the measurements are propagated through. Uncertainties in the position due to space motions increase linearly with time, but the uncertainty on the

location of the centers of the associations is dominated by their large radial extents. The kinematic parameters I used are summarized in Table 4; the space motions are shown in Figure 5.

5.2.1. ζ Oph and the Sco-Cen OB Associations

Blaauw (1991, 1993) noted that ζ Oph appears to be moving directly away from the Upper Sco association. Indeed, the space motion of ζ Oph takes it within 1.6 pc of the center of the Upper Sco association 1.0 Myr ago. This is well within the $\sim 7^\circ$ (17 pc) radial extent of the association at its distance of 140 pc. Assuming a linear expansion with time, the cluster should have been only about 20% smaller at that time, so within the uncertainties ζ Oph either passed through or originated near the center of the Upper Sco association.

However, van Rensbergen et al. (1996) have used stellar evolutionary arguments to suggest that ζ Oph is older, and originated in the Upper Cen-Lup association. They note that the space motion of ζ Oph intersects the location of the Upper Cen-Lup association 2-3 Myr in the past. From age constraints, and by modelling the atmosphere of ζ Oph, van Rensbergen et al. argue that it cannot be a single star ejected from Upper Sco by gravitational encounters with other massive stars. They could not find a binary evolution scenario that produced a star like ζ Oph in less than about 9 Myr, an age which greatly exceeds that of Upper Sco. They conclude it likely that ζ Oph was a binary in the Upper Cen-Lup association, and that it was ejected from that association when its companion star became a supernova some 2-3 Myr ago.

The space motions of ζ Oph and the Upper Cen-Lup association cast doubt on this scenario. The closest approach of the two, 30 ± 20 pc at 2.1 Myr, is only marginally consistent with origination within the ~ 30 pc (13°) radius of the association today (linear expansion suggests about a 25 pc radius at 2.1 My). Note that the Hipparcos parallaxes of ζ Oph and the two associations are virtually identical, while the radial velocities of the associations differ by about 9 km s^{-1} . The radial velocity of ζ Oph is within about 5 km s^{-1} of that of Upper Sco, but is about 13 km s^{-1} less than that of the Upper Cen-Lup association. If so, two million years ago ζ Oph would have been 30 pc further away from the Sun than was the Upper Cen-Lup association.

The -9 km s^{-1} radial velocity of ζ Oph minimizes the closest approach to the center of the Upper Sco association, while a radial velocity of $+5 \text{ km s}^{-1}$ is required to bring the star within 5 pc of the center of Upper Cen-Lup. It is unlikely that the radial velocity

measurements will be this far off, so I conclude based on geometry alone that it is not likely that ζ Oph originated in Upper Cen-Lup.

5.2.2. *The Wanderings of the Neutron Star*

One cannot be so definitive about the space motions of the neutron star, because its radial velocity is unknown and not easily measurable. Rather, I look for plausibility that the neutron star originated in one of these associations, or as companion to ζ Oph. For the measured proper motion and parallax, the neutron star comes within 7 ± 11 pc of ζ Oph at 1.2 Myr and within 12 ± 9 pc of the center of the Upper Sco association at 1.4 Myr, for a radial velocity of ~ -45 km s $^{-1}$. The closest approach of the neutron star to the Upper Cen-Lup association is 32 ± 14 pc at 1.3 Myr, for a radial velocity of ~ -35 km s $^{-1}$. These distances are summarized in Table 5.

At 90% confidence, for a radial velocity of -45 km s $^{-1}$, the positions of the neutron star, ζ Oph, and the center of the Upper Sco association all come together between 1.0 and 1.3 Myr ago. For no plausible combination of radial velocity and current distance do the NS, ζ Oph, and the center of the Upper Cen-Lup association ever coincide within 90% confidence.

It is unlikely that the spatial coincidence of ζ Oph, the Upper Sco association, and the neutron star some 1.2 Myr in the past is a mere coincidence. Given a neutron star at the position of RX J185635-3754, the likelihood that a random motion will cause it to coincide *in projection only* with the Upper Sco association ($\sim 7^\circ$ radius) is about 0.007. Therefore I identify the neutron star as the possible remnant of the original primary of the ζ Oph system. That the temperature of the neutron star is close to that expected from the standard neutron star cooling curve at 1 Myr may be further circumstantial evidence supporting this identification.

5.2.3. *PSR B1929+10*

RX J185635-3754 is not the only neutron star moving away from the general direction of the Sco-Cen complex. The nearby pulsar PSR B1929+10 (PSR J1932+1059) is another candidate for ejection from Upper Sco (Portegies Zwart, private communication). Downes & Reichley (1983) reported the proper motion. There are 3 available distances (summarized

by Pavlov et al. 1996a); I adopt Backer & Sramek’s (1981) lower limit of 250 pc ³. The spindown age is 3 Myr. Applying the same techniques used above, pulsar approaches to within 18 ± 21 pc of ζ Oph 0.9 Myr in the past, and is 21 ± 21 pc from the center of the Upper Sco association at about the same time, if the pulsar is now at a distance of 250 pc and has a radial velocity of 160 km s^{-1} . Clearly this pulsar is also a possible candidate for a binary companion to ζ Oph, since the same arguments as put forth above for the chance coincidence apply. Both cannot be the companion. Perhaps there was more than one supernova in a binary system in Upper Sco about 1 million years ago.

5.3. Kick Velocity of the Neutron Star

If RX J185635-3754 is indeed the former companion of ζ Oph, then their space motions provide sufficient information to estimate the kick velocity of the neutron star. They are separating at an angle of 69° . In the frame of the Upper Sco association, the space velocities of ζ Oph and the neutron star are 34 km s^{-1} and 84 km s^{-1} , respectively. I assume that the velocity of ζ Oph was its orbital velocity at the time the supernova unbound the system.

Evolutionary models (e.g., van Rensbergen et al. 1996) suggest that ζ Oph has a mass of 20-25 M_\odot . If the immediate progenitor of the supernova was a 4-5 M_\odot helium star, then the mass ratio would have been about 4 or 5 to 1, with ζ Oph the more massive star. Ignoring the momentum of the 3-4 M_\odot of material lost in the explosion, the remnant should have a space velocity directed anti-parallel to that of ζ Oph, with a speed higher by the mass ratio. To convert this into the observed space velocity of the neutron star requires a kick velocity of about 200 km s^{-1} directed 25° from the direction of motion of ζ Oph. A lower initial mass ratio requires a lower kick velocity; if the star that exploded was twice the mass of ζ Oph, the kick velocity is 90 km s^{-1} directed 60° from the direction of motion of ζ Oph.

6. Conclusions

RX J185635-3754 is confirmed to be an isolated neutron star, at a distance of 61_{-8}^{+9} pc, with a heliocentric space velocity of $88_{-7}^{+13} \text{ km s}^{-1}$. It appears to have left the Upper Sco OB association $1.15 \pm .15$ million years ago. It may have been the binary companion of

³The 170 pc distance suggested by the dispersion measure may be suspect because the galactic model does not account for small scale irregularities in the electron distribution (Taylor & Cordes 1993).

the runaway O star ζ Oph, which left Upper Sco at the same time. If so, the neutron star suffered a kick velocity of about 200 km s^{-1} amplitude at birth.

Reexamination of the space motions of ζ Oph and the Sco-Cen OB association casts some doubt on van Rensenbergen et al.’s conclusion that ζ Oph originated in the Upper-Cen-Lup association. It is not clear how to reconcile their binary evolutionary scenarios with these geometric constraints.

The existence of an old, isolated neutron star of known age permits one to place another point on the cooling curve, a point not contaminated by possible non-thermal emission. The exact temperature depends on the choice of atmospheric model, but in any event the temperature lies above the FP (Friedman & Pandharipande 1981) cooling curve by about a factor of 2. A number of reheating mechanisms could account for this difference.

The inferred radius of the neutron star depends on the angular diameter, which is model-dependent. The smallest angular diameter for a given temperature is given by a black body. For a temperature $kT=49 \text{ eV}$, the lower bound on the radius R_∞ is $6.0^{+1.2}_{-0.6} \text{ km}$, and preliminary atmospheric models yield $R_\infty = 11.2 \pm 3.4 \text{ km}$.

RX J185635-3754 will make its closest approach to the Earth in about 350,000 years, at a distance of $53 \pm 10 \text{ pc}$, in the constellation Grus.

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REFERENCES

- Arnett, W.D., Schramm, D.N., & Truran, J.W. 1989, ApJ, 339, L25
- An, P. 2000, Neutron Star Atmospheres and Spectral Analysis, PhD thesis, SUNY Stony Brook
- Anderson, J. & King, I.R. 1999, PASP, 111, 1095.
- Blaauw, A. 1991, in The Physics of Star Formation and Early Stellar Evolution, ed. C.J. Lada & N.D. Kylafis (Dordrecht: Kluwer), 125
- Blaauw, A. 1993, in ASP Conf. Ser. 35, Massive Stars: Their Lives in the Interstellar Medium, ed. J.P. Cassinelli & E.B. Churchwell (San Francisco: ASP) 207.

- Belloni, T., Zampieri, L., & Campana, S. 1997, *A&A*, 319, 525
- Blaes, O. & Madau, P. 1993, *ApJ*, 403, 690
- Brazier, K.T. & Johnston, S. 1999, *MNRAS*, 305, 671
- Campana, S., Mereghetti, S., & Sidoli, L. 1997, *A&A*, 320, 783
- Caraveo, P.A., Bignami, G.F., & Trümper, J.E. 1996, *A&A Rev.*, 7, 209
- Chakrabarty, D., Pivovarov, M.J., Hernquist, L.E., Heyl, J.S., & Narayan, R. 2000, *ApJ*, submitted (astro-ph/0001026)
- Downes, G.S. & Reichley, P.E. 1983, *ApJS*, 53, 169
- ESA, 1997, *The Hipparcos and Tycho Catalogues*, ESA SP-1200
- Evans, D.S. 1979, *IAU Sym* 30, p.57
- Friedman, B. & Pandharipande, V.R. 1981, *Nucl. Phys. A*, 361, 502
- Gaensler, B.M., Bock, D.C.-J., & Stappers, B.W. 2000, *ApJ*, 537, L35
- Geppert, U., Page, D., & Zannias, T. 1999, *A&A*, 345, 847
- de Geus, E.J., de Zeeuw, P.T., & Lub, J. 1989, *A&A*, 216, 44
- Greiner, J. 1996 in *Supersoft X-Ray Sources*, ed. J. Greiner (Garching: MPE), 472, 285
- Haberl, F. & Titarchuk, L. 1995, *A&A*, 299, 414
- Heyl, J.S. & Kulkarni, S.R. 1998, *ApJ*, 506, L61
- Holtzmann, J. et al. 1995, *PASP*, 107, 156
- Kaaret, P., Ford, E.C., & Chen, K. 1997, *ApJ*, 480, L27
- Knude, J. & Høg, E. 1998, *A&A*, 338, 897
- Landsman, W.B. 1995, in *ASP Conf. Ser. 77, Astronomical Data Analysis Software and Systems IV*, ed. R.A. Shaw, H.E. Payne, & J.J.E. Hayes (San Francisco: ASP), 437
- Larson, L.B., & Link, B. 1999, *ApJ*, 521, 271
- Lattimer, J.M. & Prakash, M. 1998, in *Eigtheenth Texas Symposium on Relativistic Astrophysics and Cosmology*, ed. A.V. Olinto, J.A. Frieman, & D.N. Schramm (Singapore: World Scientific), 589
- Lattimer, J.M. & Prakash, M. 2000, *ApJ*, in press (astro-ph/0002232)
- Manning, R.A., Jefferies, R.D., & Willmore, A.P. 1996, *MNRAS*, 278, 577
- Maracco, H.G. & Rydgren, A.E. 1981, *AJ*, 86, 62
- Miller, M.C., Lamb, F.K., & Psaltis, D. 1998, *ApJ*, 508, 791

- Narayan, R. & Ostriker, J.P. 1990, *ApJ*, 352, 222
- Pavlov, G.G., Stringfellow, G.S., & Córdoba, F.A. 1996a, *ApJ*, 467, 370
- Pavlov, G.G., Zavlin, V.E., Trümper, J., & Neuhäuser, R. 1996b, *ApJ*, 472, L33
- Rajagopal, M. & Romani, R. 1996, *ApJ*, 461, 327
- Taylor, J.H. & Cordes, J.M. 1993, *ApJ*, 411, 674
- Thompson, C. & Duncan, R.C. 1995, *MNRAS*, 275, 255
- Tsuruta, S. 1998, *Phys. Rep.*, 292, 1
- Turon, C. et al. 1993, *Hipparcos Input Catalog*, ESA SP-1136
- Turolla, R. 1997, in *Second International A.D. Sakharov Conference on Physics*, ed. A.J. Dremin & A.M. Semikhatov, (Singapore:World Scientific), 182
- Strohmayer, T.E., Swank, J.H., Zhang, W., White, N.E., & Lapidus, I. 1997, *BAAS*, 191, #113.03
- Vasisht, G., Kulkarni, S.R., Anderson, S.B., Hamilton, T.T., & Kawai, K. 1997, *ApJ*, 476, L43
- van Rensenbergen, W., Vanbeveren, D., & de Loore, C. 1996, *A&A*, 305, 825
- Walter, F.M. & An, P. 1998, *BAAS*, 192, #50.04
- Walter, F.M., An, P., Lattimer, J., & Prakash, M. 2000, in *Proc. of IAU Symp. #195, Highly Energetic Physical Processes and Mechanisms for Emission from Astrophysical Plasmas*, ed. P.C.H. Martens, S. Tsuruta, & M.A. Weber (San Francisco: ASP), 437
- Walter, F.M. & Matthews, L.D. 1997, *Nature*, 389, 358
- Walter, F.M., Wolk, S.J., & Neuhäuser, R. 1996, *Nature*, 379, 233
- de Zeeuw, P.T., Hoogerwerf, R., de Bruijne, J.H.J., Brown, A.G.A., & Blaauw, A. 1999, *AJ*, 117, 354
- Zhang, W., Strohmayer, T.E., & Swank, J.H. 1997, *ApJ*, 482, L167

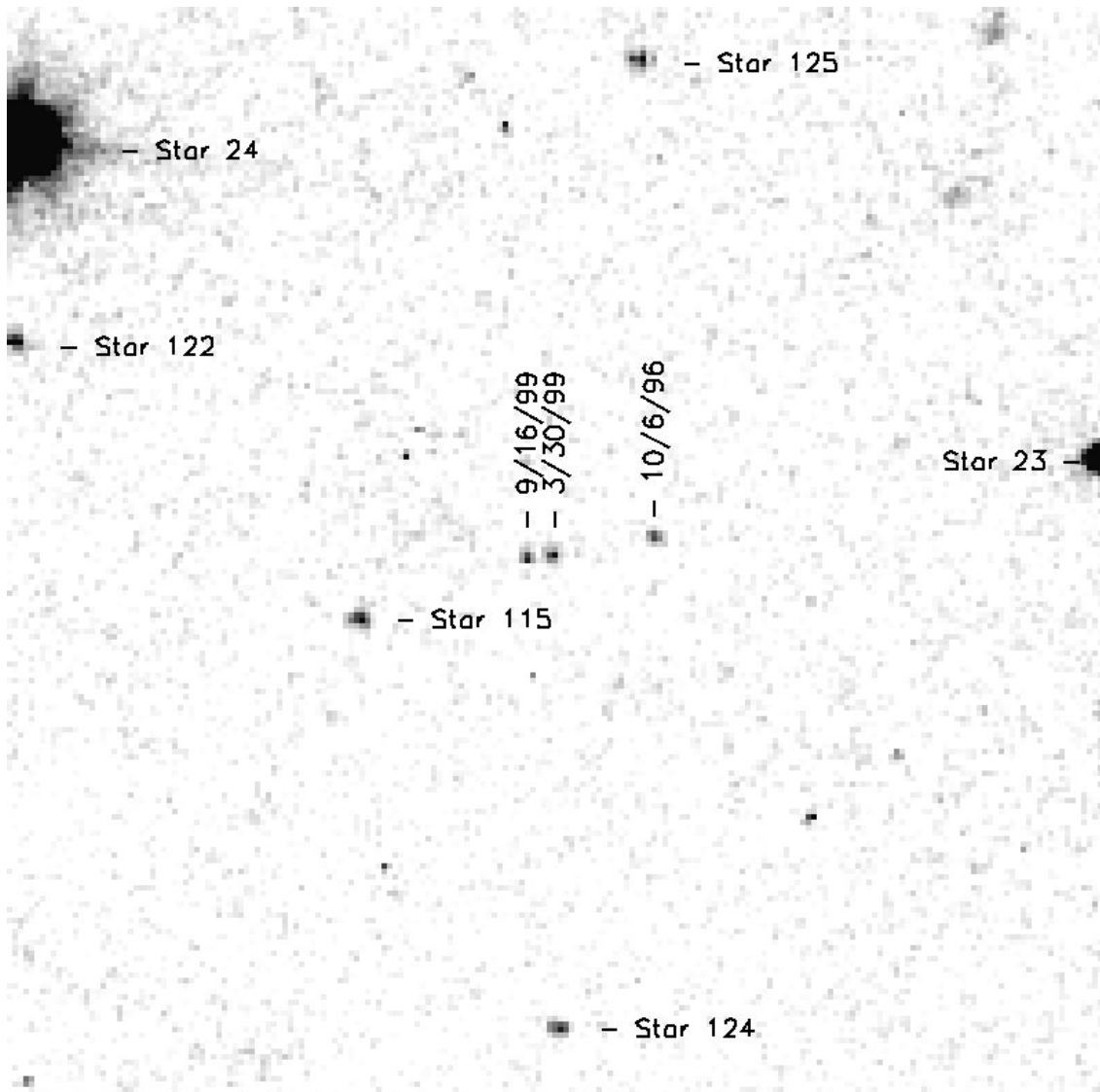


Fig. 1.— The motion of RX J185635-3754. This is an exposure-weighted sum of the three F606W images. North is up, east is to the left. The image is 9.1 arcsec (200 PC pixels) across. The three images were rotated, coaligned (to the nearest pixel) by cross-correlation, and co-added. The three images of the neutron star are labelled by date. Other stars in the image are labelled; these are slightly elongated E-W due to the simple alignment procedure.

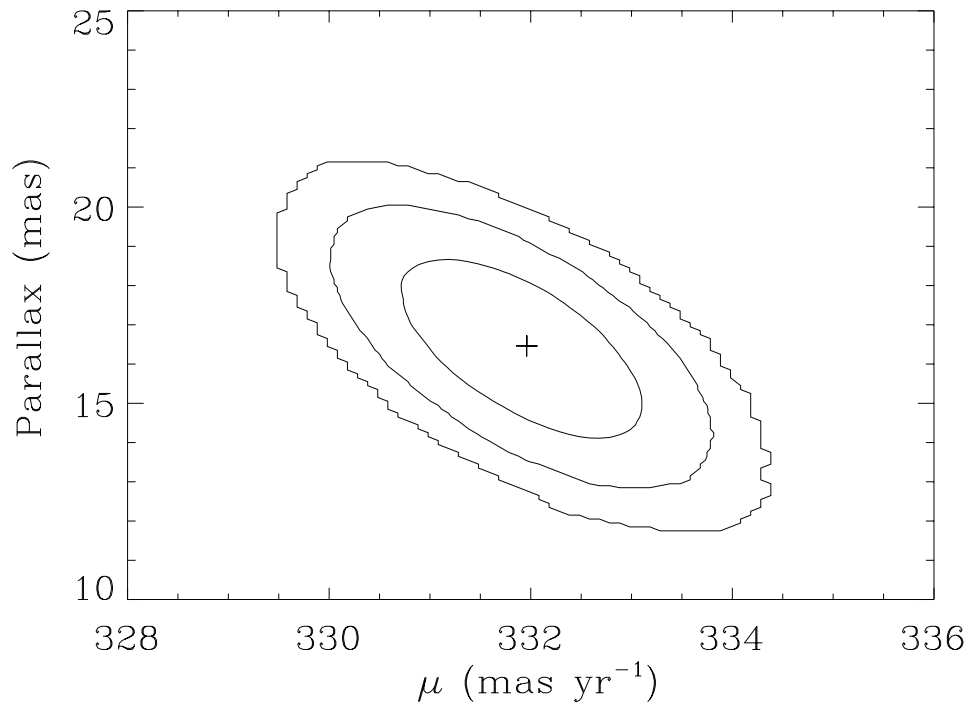


Fig. 2.— The joint confidence contours for the proper motion and the distance. The 68% (1σ), 95% (2σ), and 99.9% (3σ) confidence contours are plotted; the best estimate is marked with the plus sign.

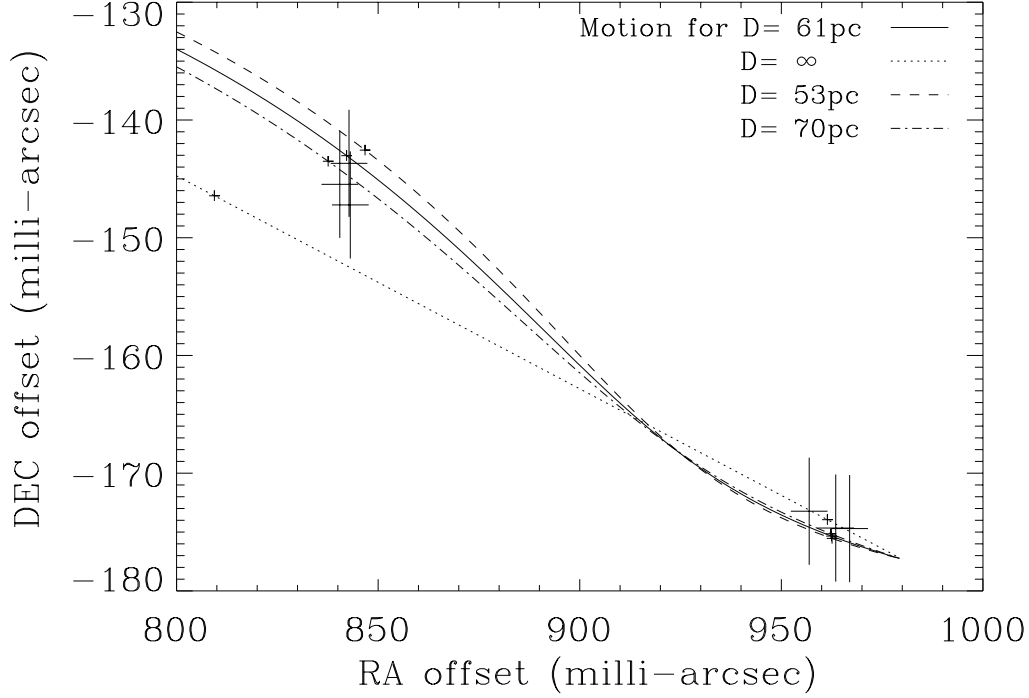


Fig. 3.— The best fit proper motion and parallax. The measured spatial offsets of the target from the initial observation (0,0) are plotted as error bars. There are 3 measurements for each observation, as described in the text. The curves show the predicted position for the nominal distance of 61 pc, for the $\pm 1 \sigma$ envelope, and for a source at infinity. The small crosses show the expected positions of the target on the day of observation. The motions in RA provide a stronger constraint on the distance than does the DEC wobble. Note that the RA and DEC scales are not the same.

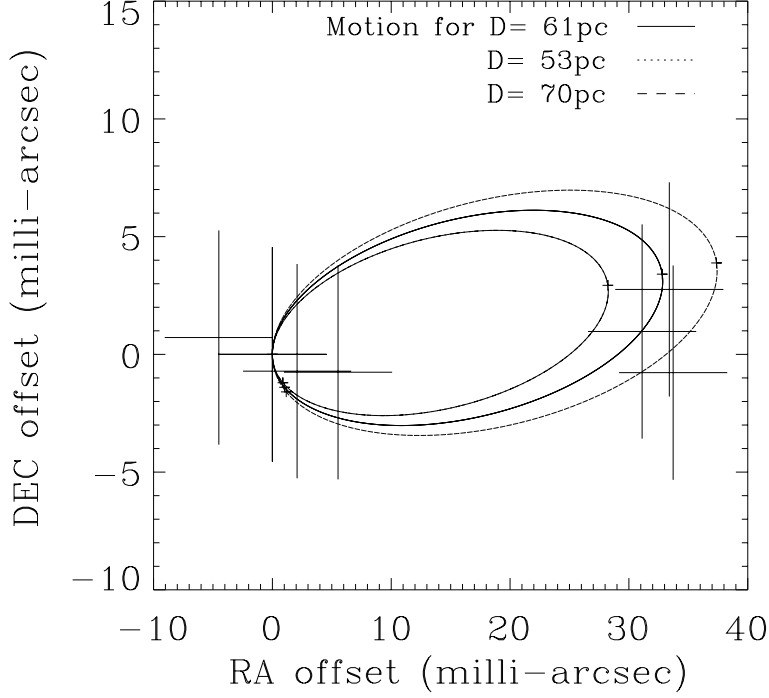


Fig. 4.— The parallactic ellipse. The measured spatial offsets, with the proper motion subtracted, are plotted on the predicted parallactic ellipse for the nominal distance of 61 pc and for the $\pm 1 \sigma$ envelope. The large error bars represent the three measurements at each epoch; the point at (0,0) represents the initial observation. The small crosses show the expected positions of the target on the day of observation. Note that the RA axis is twice the length of the DEC axis.

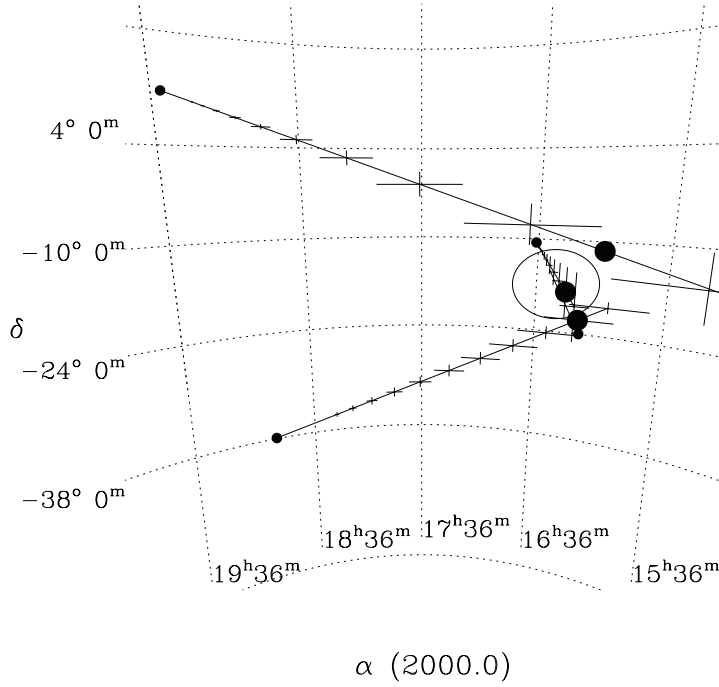


Fig. 5.— Apparent positions of the neutron star RX J185635-3754 (moving ESE), the pulsar B1929+10 (moving ENE), ζ Oph (declination -10° , moving NNE), and the Upper Sco association (declination -24° , moving SSW) projected backwards in time. I use the assumed radial velocities of -45 and $+160$ km s^{-1} for RX J185635-3754 and PSR B1929+10 which yield the closest approaches to ζ Oph. The present positions are plotted as small solid dots; positions of B1929+10, ζ Oph, and RX J185635-3754 at times of closest approach are the large filled circles. The large open circle is the position and approximate size of the Upper Sco association at the time of closest approach. The uncertainties on the positions are plotted at 10 points spaced logarithmically in time between 0.1 and 1.5 million years in the past.

Table 1. WFPC2 Observation Log

Program	Date (UT)	Root	Roll (deg)	time (sec)
6149	1996 Oct 6	U3IM01	129.5	4800
7408	1999 Mar 30	U51G01	−51.6	7200
7408	1999 Sep 16	U51G02	124.2	5191

Table 2. Objects Identified in WFPC2 Images^a

ID	RA (s) +18 ^h 56 ^s	DEC (") −(37° 54′)	M _{F606W}	Note ^b	ID	RA (s) +18 ^h 56 ^s	DEC (") −(37° 54′)	M _{F606W}	Note ^b
100	34.2647	29.977	25.1		122	35.9440	35.188	26.3	
101	34.5549	23.679	24.2		123	36.3414	37.038	26.4	
102	34.5906	22.338	24.4		124	35.5635	40.923	26.8	
103	34.8373	16.947	23.8		125	35.5023	32.800	26.6	
104	34.9456	16.308	25.4	E	126	35.8937	28.822	26.8	
105	35.4770	21.313	25.9		127	35.3542	49.328	25.9	
106	35.5512	25.310	22.3		128	35.2637	47.997	24.9	
107	34.4844	43.087	23.5		129	35.0718	44.297	26.2	
108	35.8185	47.302	25.2	E	130	35.1307	14.480	26.4	
109	35.5538	42.777	25.7	E	131	35.1498	17.022	26.4	
110	36.0382	46.799	25.0		132	34.4582	25.389	26.3	
111	37.0722	29.560	24.5		133	35.3043	29.448	20.2	
112	36.3679	24.570	23.6		19	34.2052	40.171	21.9	1
113	36.1096	33.936	23.8		20	35.0369	39.048	24.0	1; E
114	35.9229	31.175	24.2		21	34.7937	37.178	20.9	1
115	35.7030	37.480	26.5		23	35.1855	36.142	23.7	1
116	33.6869	36.232	24.0		24	35.9404	33.506	20.3	1
117	34.5558	23.072	25.7		26	36.8333	29.630	21.4	1
118	34.9533	25.884	24.6		28	34.8730	29.639	21.5	1
119	35.6693	24.284	25.7		I	35.2597	14.740	18.9	2
121	36.0028	35.401	26.0		J	34.7934	25.762	20.9	2
X	35.5003	36.823	25.9	3					

^aThese positions are measured on the U3IM01 image. The coordinates are equinox J2000, epoch 1996.75.

^b(1): ID from Campana et al. 1997; (2): ID from Walter et al. 1996.; (3): the target, RX J185635-3754; E: extended source, probably a galaxy.

Table 3. The Motions of RX J185635-3754

Quantity		68% confidence	95% confidence	
Proper Motion (α)	326.7	± 0.8	± 1.5	mas yr ⁻¹
Proper Motion (δ)	-59.1	± 0.7	± 2.2	mas yr ⁻¹
Proper Motion	332.0	$^{+1.1}_{-1.3}$	$^{+1.8}_{-2.0}$	mas yr ⁻¹
Position Angle	100.3	± 0.1	± 0.3	°
Parallax	16.5	$^{+2.4}_{-2.2}$	$^{+3.7}_{-3.5}$	mas

Table 4. Space Motions of ζ Oph and the Sco Cen Associations^a

Quantity	ζ Oph	Upper Sco	Upper Cen-Lup
Distance	140^{+16}_{-12}	145 ± 3	142 ± 2 pc
Proper Motion (α)	13.07 ± 0.85	-10.89 ± 2.3	-21.06 ± 5.1 mas yr ⁻¹
Proper Motion (δ)	25.44 ± 0.72	-23.39 ± 3.6	-23.35 ± 3.8 mas yr ⁻¹
radial velocity	-9 ± 5	-4.6 ± 1.7	4.9 ± 1.7 km s ⁻¹

^aSources are referenced in the text.

Table 5. Close Approaches

Encounter	Distance (pc)	Time (Myr)	RV_{NS}^a (km s ⁻¹)	D_{NS}^b (pc)
ζ Oph - Upper Sco	2 ± 15	1.0
ζ Oph - Upper Cen-Lup	31 ± 21	2.1
For nominal neutron star distance of 61 pc				
NS- ζ Oph	7 ± 11	1.2	-45	...
NS - Upper Sco	12 ± 9	1.4	-45	...
NS - Upper Cen-Lup	32 ± 14	1.3	-35	...
For unconstrained neutron star distance				
NS- ζ Oph	1 ± 16	1.8	-45	44
NS- Upper Sco	5 ± 8	0.5	+25	130
NS- Upper Cen-Lup	4 ± 15	3.0	-25	24

^a The neutron star (NS) radial velocity which minimizes the distance of closest approach.

^b The present distance of the neutron star which minimizes the distance of closest approach.